

DISCOVERY OF THE PRE-MAIN SEQUENCE POPULATION OF THE STELLAR ASSOCIATION LH 95 IN THE LARGE MAGELLANIC CLOUD WITH HUBBLE SPACE TELESCOPE ACS OBSERVATIONS^{1,2}

DIMITRIOS A. GOULIERMIS³, THOMAS HENNING³, WOLFGANG BRANDNER^{3,4},
ANDREW E. DOLPHIN⁵, MICHAEL ROSA^{6,7}, AND BERNHARD BRANDL⁸

Accepted for publication in ApJ

ABSTRACT

We report the discovery of an extraordinary number of pre-main sequence (PMS) stars in the vicinity of the stellar association LH 95 in the Large Magellanic Cloud (LMC). Using the *Advanced Camera for Surveys* on-board the *Hubble* Space Telescope in wide-field mode we obtained deep high-resolution imaging of the main body of the association and of a nearby representative LMC background field. These observations allowed us to construct the color-magnitude diagram (CMD) of the association in unprecedented detail, and to decontaminate the CMD for the average LMC stellar population. The most significant result is the direct detection of a substantial population of PMS stars and their clustering properties with respect to the distribution of the higher mass members of the association. Although LH 95 represents a rather modest star forming region, our photometry, with a detection limit $V \lesssim 28$ mag, reveals in its vicinity more than 2,500 PMS stars with masses down to $\sim 0.3 M_{\odot}$. Our observations offer, thus, a new perspective of a typical LMC association: The stellar content of LH 95 is found to extend from bright OB stars to faint red PMS stars, suggesting a fully populated Initial Mass Function (IMF) from the massive blue giants down to the sub-solar mass regime.

Subject headings: Magellanic Clouds — open clusters and associations: individual (LH 95) — stars: formation — stars: pre-main sequence — Hertzsprung-Russell diagram — HII regions

1. INTRODUCTION

The Large and Small Magellanic Cloud (LMC, SMC) are the closest undisrupted neighboring dwarf galaxies to our own. Both the Magellanic Clouds (MCs) offer an outstanding variety of young stellar associations, the age and IMF of which become very important sources of information on their recent star formation. Stellar associations contain the richest sample of young bright stars in a galaxy. Consequently our knowledge on the young massive stars of the MCs has been collected from photometric and spectroscopic studies of young stellar associations (Massey 2006). However, a more comprehensive picture of these stellar systems has emerged when *Hubble* observations revealed that MCs associations host also large numbers of faint pre-main sequence (PMS) stars.

Nearby galactic OB associations are known to be significant hosts of PMS stars (e.g. Preibisch et al. 2002; Briceño et al. 2007). The optical study of significant numbers of such stars in the MCs can only be achieved at the angular resolution and wide-field facilitated with *Hubble*. Indeed, Gouliermis et al. (2006a) presented, for the first time, such a study in the case of the LMC association LH 52, where they identified

the candidate low-mass PMS population of the system with HST/WFPC2 observations in $F555W$ and $F814W$ filters. The locations of the detected PMS stars of LH 52 on the $V-I$, V CMD are found to be in excellent agreement with the ones of T Tauri stars with $M \lesssim 2 M_{\odot}$ in the Ori OB1 association in the Galaxy (Sherry et al. 2004; Briceño et al. 2005). As far as associations in the SMC are concerned, Brandner et al. (1999) originally reported the detection of about 150 objects with excess emission in $H\alpha$ in a $2' \times 2'$ field slightly off the brightest stars of the association NGC 346. They explained this detection as an indication that this system hosts PMS stars with masses between 1 and $2 M_{\odot}$. More recently, HST/ACS observations allowed Nota et al. (2006) and Gouliermis et al. (2006b) to verify that indeed there is a prominent population of low-mass PMS stars located in this association.

In this letter we report the discovery of the PMS stellar content of another LMC association, LH 95 (Lucke & Hodge 1970), related to the H II region LHA 120-N 64, or in short N 64 (Henize 1956). The significance of this discovery lies in the fact that our observations, being the deepest ever obtained with the *Hubble* of a star forming stellar system in the MCs, reveal an extraordinary rich sample of faint red (with $M \gtrsim 0.3 M_{\odot}$), as well as more massive (with $M \lesssim 7 M_{\odot}$) but short-lived PMS stars. In §2 we describe the data used in this study, and in §3 we present the discovery of these stars and a typical CMD of an LMC association, as our new *Hubble* data reveal it. We also discuss the spatial distribution of these stars. A short summary and future prospects are given in §4.

2. OBSERVATIONS AND PHOTOMETRY

The data used in this study were collected within our HST GO Program 10566. Two pointings (with significant offsets) were observed with the Wide-Field Channel (WFC) of the *Advanced Camera for Surveys* (ACS) in the filters $F555W$ and $F814W$, equivalent to standard V and I respectively. The first pointing is centered on the association LH 95. The second

¹ Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

² Research supported by the German Research Foundation (Deutsche Forschungsgemeinschaft) and the German Aerospace Center (Deutsches Zentrum für Luft und Raumfahrt).

³ Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany

⁴ UCLA, Div. of Astronomy, 475 Portola Plaza, Los Angeles, CA 90095-1547, USA

⁵ Raytheon Corporation, USA

⁶ Space Telescope European Coordinating Facility, ESO, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

⁷ Affiliated to the Space Telescope Operations Division, RSSD, ESA.

⁸ Leiden University, Leiden Observatory, Niels Bohrweg 2, P.O. Box 9513 2300 RA Leiden, The Netherlands

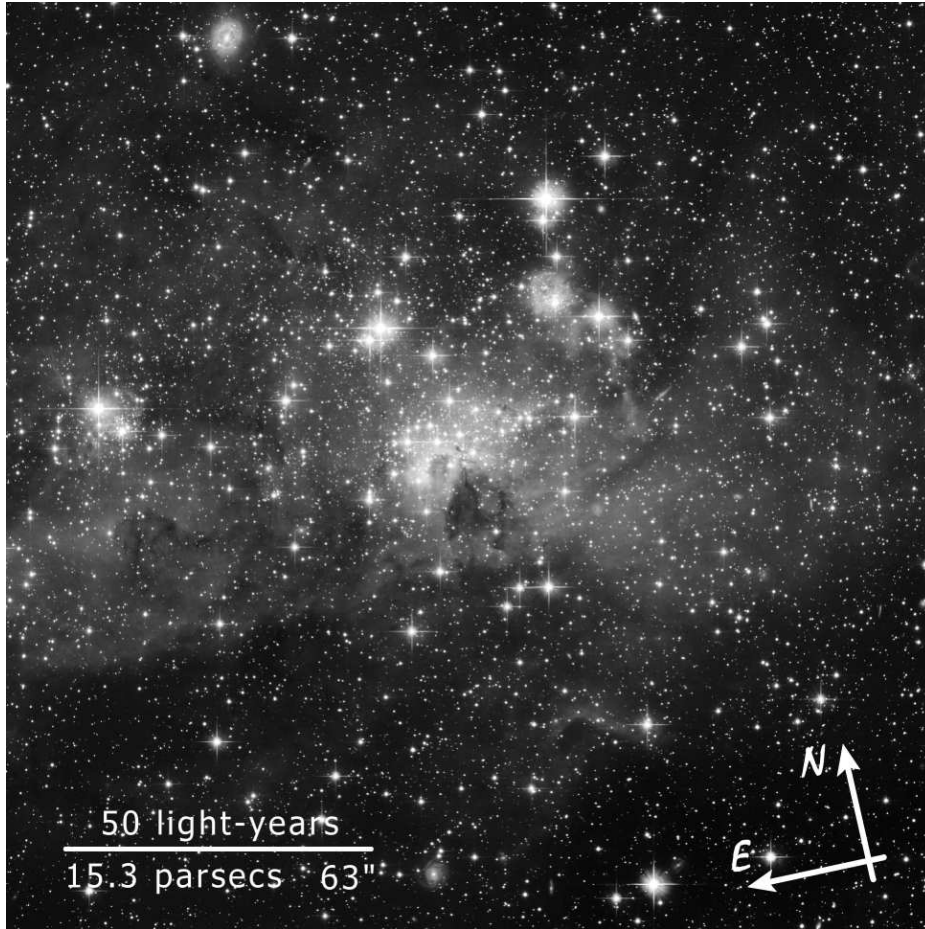


FIG. 1.— Color-composite image from ACS/WFC observations in the filters $F555W$ and $F814W$ (V - and I -equivalent) of the LMC star-forming region LH 95/N 64. This image reveals a large number of low-mass infant PMS stars coexisting with young massive ones. The smooth continuum in the image is due to the gas emission from the H II region, which is partly included in the $F555W$ filter.

pointing is located $\sim 2'$ to the west, on a nearby “empty” area, selected as the most representative of the local background field of the LMC. We refer to these observed fields simply as the “system” and the “field”, respectively. A color-composite image of the pointing on the system is shown in Figure 1. These observations, being among the deepest ever taken towards the LMC, allow us to explore the scientific gain that can be achieved for the study of resolved extragalactic stellar populations using high spatial resolution photometry from *Hubble*⁹.

Photometry was obtained using the ACS module of the package DOLPHOT¹⁰ (Ver. 1.0). We followed the photometric process as it is described by Gouliermis et al. (2006b) for similar observations of the association NGC 346 in the SMC. One of the advantages of DOLPHOT is the ability to perform photometry simultaneously for all exposures. We did this using the $F814W$ drizzled frame as the position reference for the detected stars. Photometric calibrations and transformations were made according to Sirianni et al. (2005), and CTE corrections were made according to ACS ISR 04-06. A

complete account of the photometric procedure will be given in a subsequent paper. After cleaning bad detections based on DOLPHOT’s star quality parameters, more than 16,000 stars were detected in the system and 17,000 in the field. The completeness of the data was evaluated by artificial star experiments, that were performed by running DOLPHOT in artificial star mode. The completeness, which reach the limit of 50% at $V \approx 28$ mag in the system, as well as the photometric uncertainties, which are $\sigma \lesssim 0.1$ mag for $V \lesssim 27.5$ mag, will be also discussed in detail in a subsequent paper.

3. DETECTION OF THE PRE-MAIN SEQUENCE STARS

3.1. Color-Magnitude Diagrams

The $V-I$, V Color-Magnitude Diagram (CMD) of the detected stars in both the system and the field is shown in Figure 2 (*left* and *middle* panel, respectively). This figure shows that both regions provide excellent examples of well resolved extra-galactic stellar populations, with the CMDs being characterized by the coexistence of different stellar species. In the CMD of the system (Figure 2 *left*) there is a sharp upper main sequence (UMS) of young blue massive stars, which is characteristic of LMC associations. There is a bright cut-off in the CMD of the field (Figure 2 *middle*), because of the lack of short exposures, but previous ground-based photometry by Gouliermis et al. (2002) has shown that this area does not include any UMS stars. On the other hand, a pronounced

⁹ Press releases related to this study can be found at www.spacetelescope.org/news/html/heic0607.html and hubblesite.org/newscenter/archive/releases/2006/55/.

¹⁰ The ACS mode of DOLPHOT is an adaptation of the photometry package HSTphot (Dolphin 2000). It can be found with its documentation at <http://purcell.as.arizona.edu/dolphot/>.

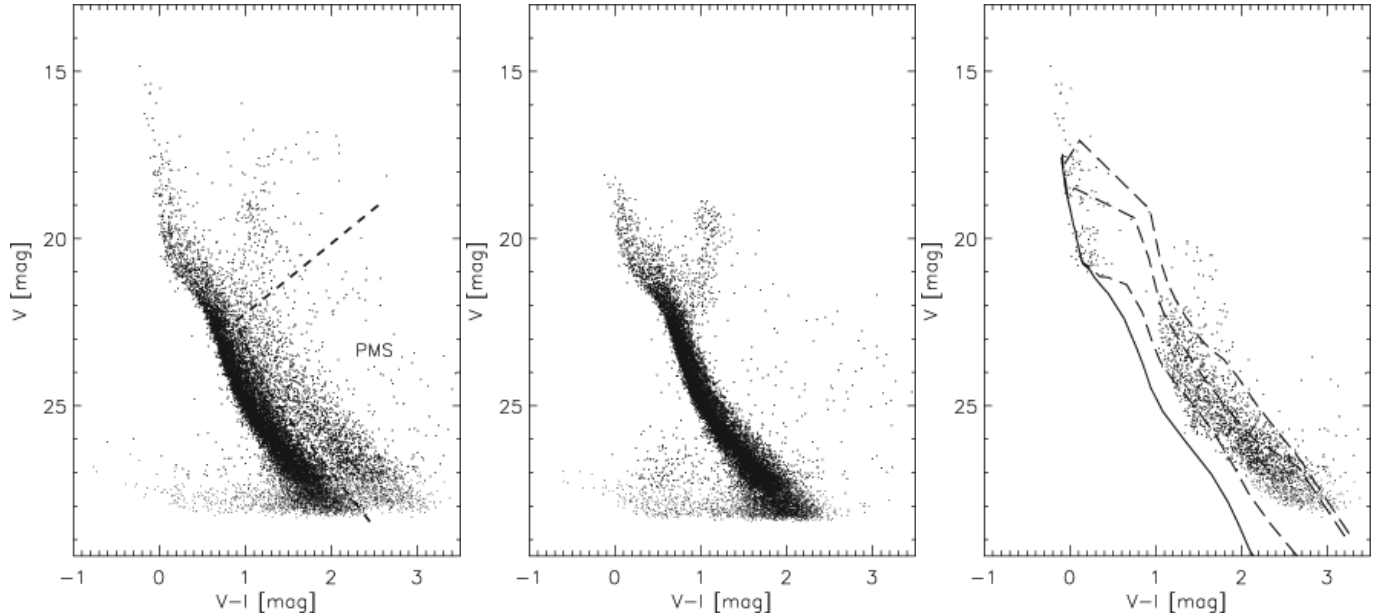


FIG. 2.— The $V-I$, V CMDs of the stars detected with our photometry in the system (left) and the field (middle). The comparison of these CMDs exhibits the differences in stellar content of the two observed fields, and demonstrates the richness of PMS stars in the vicinity of a LMC stellar association, as it is emphasized by the complete lack of such stars in the LMC field. This is clearly shown in the CMD of the association after the contaminating stellar population of the LMC field has been statistically subtracted (right). Three PMS isochrones (for ages 0.5, 1.5 and 10 Myr; dashed lines) as well as the ZAMS (solid line) from Siess et al. (2000) grid of models are overplotted. These models suggest that PMS stars of masses from $\sim 7 M_{\odot}$ down to $\sim 0.3 M_{\odot}$ (within 50% completeness) exist in the association. In all CMDs stars with the best photometry ($\sigma \leq 0.1$ mag in both bands) are plotted with thick symbols.

turn-off at around $V \simeq 22.5$ mag and a red giant branch (RGB) with its red clump clearly located at around $V \simeq 19$ mag and $V-I \simeq 1.2$ mag, typical of the LMC field (e.g. Elson et al. 1997; Smecker-Hane et al. 2002) can be seen in both CMDs. Below the turn-off, moving to fainter magnitudes, the main sequence in both CMDs is increasingly densely populated with what appears to be a well mixed collection of low main sequence (LMS) stars. However, apart from the UMS, a striking difference between the two CMDs exists in the red part of the LMS, where a prominent sequence of PMS stars can be seen in the CMD of the system, but is completely absent from the field.

A first-order selection of the part of the CMD occupied by these stars, as it is drawn with a thick dashed line in Figure 2 (left), reveals the extraordinary number of at least 2,500 PMS stars in the $3'4 \times 3'4$ wide area of this rather quiescent star forming region in the LMC. Moreover, the locations of these PMS stars in the CMD fit very well the ones of the PMS stars previously discovered in other MCs associations (e.g. Gouliermis et al. 2006a,b), and they match the ones of T Tauri stars as they have been observed over relatively similar wavelengths in OB associations of the Galaxy (Sherry et al. 2004; Bricenõ et al. 2005). It should be noted that although there are conspicuous dust clouds within the association (Figure 1), the interstellar reddening in the region is not high enough to cause the apparent difference at the PMS part of the CMD between the system and the field.

3.2. The CMD of the Stellar Association

Both areas of the system and the field were observed with identical setup of the instrument, dithering and exposure times. However, for the system a few additional short exposures were taken to handle over-exposed stars in the brightest upper part of the CMD. The identical observing procedures for system and field allows us a direct decontamination of the

system CMD from the contribution of the local LMC field, as it is captured in the CMD of the field. We perform this process by applying a Monte Carlo subtraction method. Specifically, we divided the CMDs of both areas in similar sets of subregions, and we statistically subtracted from the CMD of the area of the system the corresponding number of randomly selected stars in the CMD of the field for each of these subregions. The derived “clean” CMD of the association alone is shown in Figure 2 (right), where it is verified that indeed it is the UMS and PMS populations that define such systems. According to PMS isochrone models by Siess et al. (2000) the PMS stars of LH 95 cover a mass-range down to $0.3 M_{\odot}$ (within 50% completeness). It should be noted, though, that in this CMD we cannot detect the turn-on as it would be expected by the overplotted models. This is because this part of the CMD coincides with the turn-off of the field population, which is quite rich (as is seen in both left and middle panels of Figure 2). A more detailed study of the contamination of the turn-on by the turn-off will be performed in a forthcoming paper.

3.3. PMS sub-clusters in Stellar Associations of the LMC

In order to visualize the spatial distribution of the various stellar content within the system we performed star counts on our catalog of detected stars in square grids, under the assumption that each star is a point determined by its coordinates in the catalog. The binning was done so that each grid element has dimensions $\simeq 216$ WFC pixels, or $\simeq 10''$, which corresponds to about 2.5 pc at the distance of the LMC. This technique allows the construction of detailed maps of the spatial density distributions for each stellar group (isodensity contour maps). The constructed contour maps for the UMS, PMS and LMS are shown in Figure 3. Surface density is plotted in steps of 1σ , where σ is the standard deviation of the background density, starting from the 1σ isopleth.

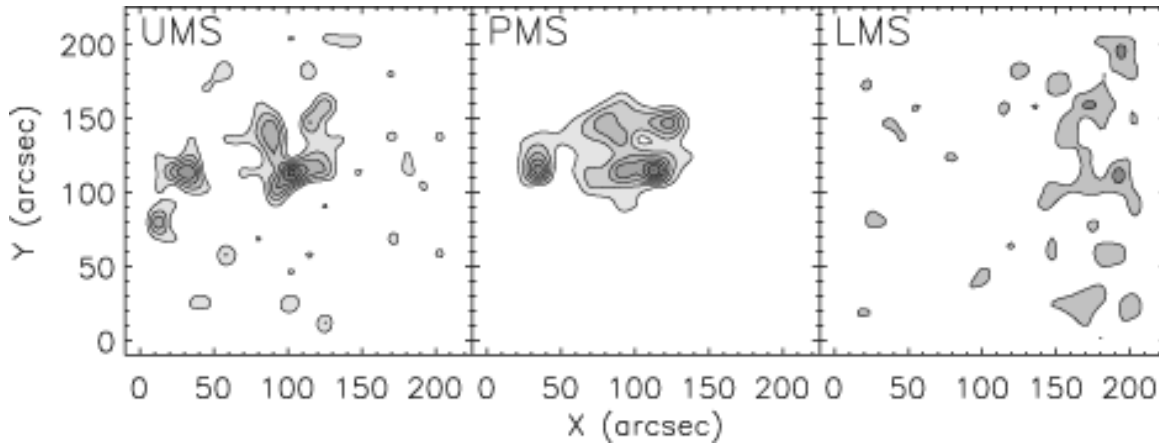


FIG. 3.— Isodensity contour maps constructed from star counts of three different stellar populations, which cover different regions in the CMDs of Figure 2 (UMS, PMS, and LMS). From these maps it is shown that PMS stars are forming compact subgroups, which coincide with the higher concentrations of UMS stars as well. LMS, as well as RGB, stars do not appear with any statistical significance in the region of the system, probably due to foreground extinction by the dust and crowding.

Any stellar concentration with density equal or higher than 3σ above the background density (third isopleth in the maps of Figure 3) is considered to be statistically significant. One can see that both, the UMS and the PMS stars are non-uniformly distributed within LH 95. Their spatial distribution is quite clumpy on the scale of $20''$ (~ 5 pc), and both species form several density peaks, four of which coincide between the UMS and PMS maps. This clearly suggests that the PMS stars are concentrated in small clusters, which are characterized by bright massive stars. These PMS clusters do not show to be physically independent to each other, but they probably are subgroups of the association itself. This is a typical case also for local OB associations in our galaxy (Bricen  et al. 2007). As far as the LMS concerns, their isodensity contour map shown in Figure 3 (*right*) indicates that these stars do not form any significant concentrations in the area of LH 95. This is also the case for the RGB stars.

4. SUMMARY

We take advantage of the large improvement in sensitivity and wide-field resolution provided by ACS to perform a detailed photometric study of the star-forming region LH 95/N 64 in the LMC. We performed photometry on two WFC pointings, $3/4 \times 3/4$ each, centered on the association LH 95 and a nearby representative background field. Since both pointings were observed with similar telescope settings, the derived photometric catalogs provide a coherent stellar sample for both observed regions, allowing us to remove accurately the contamination of the field from the CMD of the system with the use of a Monte Carlo technique.

These one-of-a-kind observations dramatically enhance the picture we have had up until now for stellar associations in the Magellanic Clouds by revealing a unique rich sample of more than 2,500 low- and intermediate-mass PMS stars (with $7 \lesssim M \lesssim 0.3 M_{\odot}$) in LH 95/N 64. Our data revealed, thus, the complete CMD of a stellar association in the LMC from the massive regime populated by the brightest UMS stars down to the lowest masses ever observed in this galaxy, where PMS stars dominate.

The spatial distribution of the PMS members of the association demonstrates the existence of significant substructure (“subgroups”), as in the case of galactic OB associations. This stellar sub-clustering has been suggested to have its origins possibly in short-lived parental molecular clouds within a Giant Molecular Cloud Complex (Bricen  et al. 2007). Each of these “PMS clusters” in LH 95/N 64 includes a few early-type stars. Such stars have been identified as candidate Herbig Ae/Be (HAeBe) stars due to their strong H α emission (Gouliermis et al. 2002). A more comprehensive study of the star-forming region of LH 95/N 64 will include the further detailed investigation of the PMS/UMS subgroups, which will be performed with the use of our ACS data in synergy with near-IR spectroscopy obtained with SINFONI on ESO/VLT.

D. A. Gouliermis kindly acknowledges the support of the German Research Foundation (Deutsche Forschungsgemeinschaft - DFG) through the individual grant 1659/1-1. We also acknowledge the contribution of M. Schmalzl through his field-subtraction Monte Carlo algorithm.

REFERENCES

- Brandner, W., Grebel, E. K., Zinnecker, H., & Brandl, B. 1999, IAU Symp. 190: New Views of the Magellanic Clouds, 190, 366
- Bricen , C., et al. 2005, AJ, 129, 907
- Bricen , C., Preibisch, T., Sherry, W. H., Mamajek, E. A., Mathieu, R. D., Walter, F. M., & Zinnecker, H. 2007, Protostars and Planets V, 345 (arXiv:astro-ph/0602446v1)
- Dolphin, A. E. 2000, PASP, 112, 1383
- Elson, R. A. W., Gilmore, G. F., & Santiago, B. X. 1997, MNRAS, 289, 157
- Gouliermis, D., Keller, S. C., de Boer, K. S., Kontizas, M., & Kontizas, E. 2002, A&A, 381, 862
- Gouliermis, D., Brandner, W., & Henning, T. 2006a, ApJL, 636, L133
- Gouliermis, D. A., Dolphin, A. E., Brandner, W., & Henning, T. 2006b, ApJS, 166, 549
- Henize, K. G. 1956, ApJS, 2, 315
- Lucke, P. B., & Hodge, P. W. 1970, AJ, 75, 171
- Massey, P. 2006, The Local Group as an Astrophysical Laboratory, 164 (arXiv:astro-ph/0307531)
- Nota, A., et al. 2006, ApJL, 640, L29
- Preibisch, T., Brown, A. G. A., Bridges, T., Guenther, E., & Zinnecker, H. 2002, AJ, 124, 404
- Sherry, W. H., Walter, F. M., & Wolk, S. J. 2004, AJ, 128, 2316
- Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
- Sirianni, M., et al. 2005, PASP, 117, 1049
- Smecker-Hane, T. A., Cole, A. A., Gallagher, J. S., & Stetson, P. B. 2002, ApJ, 566, 239